Effect of residence times on River Mondego estuary eutrophication vulnerability

A.S. Duarte*, J.L. Pinho*, M.A. Pardal, J.M. Neto** J.P. Vieira* and F.S. Santos*****

* Department of Civil Engineering, University of Minho, 4710-057 Braga, Portugal

** IMAR–Institute of Marine Research c/o Departement of Zoology, University of Coimbra, 3004-517 Coimbra, Portugal

*** Department of Civil Engineering, University of Coimbra, 3049 Coimbra Codex, Portugal

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Abstract The south arm of the Mondego estuary, located in the central western Atlantic coast of Portugal, is almost silted up in the upstream area. So, the water circulation is mostly driven by tides and the tributary river Pranto discharges. Eutrophication has been taking place in this ecosystem during last twelve years, where macroalgae reach a luxuriant development covering a significant area of the intertidal muddy flat.

A sampling program was carried out from June 1993 to June 1994. Available data on salinity profiles and on nutrients loading into the south arm were used in order to get a better understanding of the ongoing changes. River Pranto flow discharges, controlled by a sluice, were also monitored. Integral formulations are typically based on assumptions of steady state and well-mixed systems and thus cannot take into account the space and time variability of estuarine residence times, due to river discharge flow, tidal coefficients, discharge(s) location and time of release during the tidal cycle. This work presents the hydrodynamics modelling (2D-H) of this system in order to estimate the residence times variability and to assess their effect on the estuarine eutrophication vulnerability, contributing to better environmental management strategies selection.

Keywords Estuarine environment management; mathematical models; hydrodynamics; residence times; eutrophication; Mondego estuary

Introduction

The physical and chemical dynamics and the ecology of shallow estuarine areas are strongly influenced by the freshwater runoff and the adjacent open sea. The freshwater input influences estuarine hydrology by creating salinity gradients and stratification and assures large transport of silt, organic material and inorganic nutrients to the estuaries (Pardal, 1998, Flindt *et al.*, 1999). The open marine areas determine large scale physical and chemical forcing on the estuarine ecosystem, due to tide and wind generating water exchange (Berner and Berner, 1996).

Efficient water column mixing and frequent resuspension events ensure fast vertical transport of organic and inorganic matter (Pardal, 1998) integrating the pelagic and benthic food webs and the biogeochemical processes (Lillebø, 2000).

Estuarine eutrophication has increased due to massive nutrient loading from urbanised areas and diffusive runoff from intensively agricultural areas. This increased nutrient loading has severe consequences for the ecology of estuaries, due to changes in plant composition (Flindt *et al.*, 1999), which consequently affects heterotrophic organisms, specialised in living on this production (Pardal *et al.*, 2000, Lillebø *et al.*, 1999).

As a consequence of nutrient enrichment, opportunistic macroalgae growth were strongly stimulated allowing the occurrence of macroalgae blooms and the extinction of seagrass in more shallow areas. This situation may result in anoxic system collapse, with the development of hydrogen-sulphide conditions, lethal to rooted macrophytes such as *Zostera* spp. The consequence is a structural change of the ecosystem, from a grazing controlled system to a detritus/mineralisation system (Pardal, 1998), where the turnover of oxygen and nutrients is much more dynamic (Lavery and McComb, 1991), and macroalgae play an important role in the nutrient pathways of the ecosystem.

Thus, due to the importance of their impacts in the ecosystem, it becomes crucial to obtain information on the mechanisms that regulate the abundance of opportunistic macroalgae. Advective transport may be the most important process that controls the spatial and temporal distribution of macroalgae. Depending on the tidal amplitude, depth, cohesiveness of plant material, current velocity and wind-and wave-induced vertical turbulence, plants growing in shallow areas are suspended in the water column and transported out and eventually settle in deeper areas (Sfriso *et al.*, 1992, Martins *et al.*, in press). Convective transport is of major importance because it may regulate the oxic conditions in estuaries with high opportunistic macroalgae productivity.

In our case study, the occurrence of eutrophication processes seems to be dependent on the precipitation annual regime, because, in wet years, no significant growth of *Enteromorpha* spp is noted. It was decided to assess the effect of hydrodynamic conditions and salinity gradients – related with high precipitation values during winter and early spring – on estuarine eutrophication vulnerability (Vieira *et al.*, 1998).

The aim of this study is to assess the role of estuarine hydrodynamics on the non-attached macroalgae control, because the quantitative aspects of this phenomenon are not well known. A hydrodynamic model (2D-H) of Mondego estuary south arm was implemented in order to estimate residence times, current velocity and salinity distribution at different simulated scenarios, considering averaged tidal conditions. The conclusions of an early study about the macroalgae growth behaviour are also presented. In further research works, useful tools for an estuarine integrated management will be developed in order to support the decision making process (Vieira and Lijklema, 1989).

Study area

The Mondego river basin is located in the central region of Portugal, confronting with Vouga, Lis and Tagus, and Douro river basins, from the north, south and east, respectively. The drainage area is 6,670 km^2 and the annual mean rainfall is between 1,000 and 1,200 mm. This estuary (40°08’N 8°50’W) has a considerable regional importance due to the Figueira da Foz mercantile harbour, but is under severe environmental stress, namely an ongoing eutrophication process, due to human activities: industries, aquaculture farms and nutrients and chemicals discharge from agricultural lands of the low river Mondego valley (Figure 1).

This estuarine system is divided into two arms (north and south) with very different hydrological characteristics, separated by the Murraceira Island. The north arm is deeper and receives the majority of freshwater input (from the Mondego river), while the south arm of this estuary is shallower (2 to 4 m deep, during high tide, for a tidal range about 2 to 3 m) and is almost silted up in the upstream area (Figure 2). Consequently, the south arm estuary water circulation is mainly due to tides and the usually small freshwater input of Pranto river, a tributary artificially controlled by a sluice, located at 6 km from the mouth. Benthic eutrophication has been giving rise to qualitative changes in this estuary benthic community, involving the replacement of eelgrass, *Zostera noltii*, by green algae such as *Enteromorpha* spp. and *Ulva* spp.

Methods

Sampling Data

Most of the estuarine processes (physical, chemical and biological) are related to the salinity, because its variation is one of the major characteristics of an estuarine system. For the water sampling location and the benthic stations, an indication of the variability in the local salinity regime over a tidal period (for little and high river discharges) can facilitate future interpretation of the data.

Tidal movement is one of the major driving forces of this estuarine circulation in this

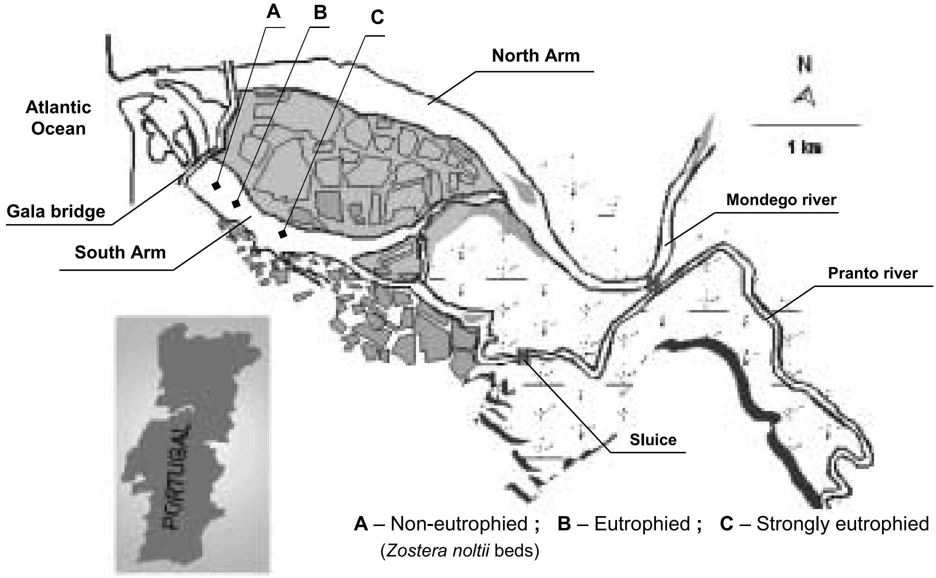

Figure 1 General layout of the river Mondego estuary and eutrophication gradient in the south arm

Figure 2 Bathymetry of the Mondego estuary south arm

system and it is also visible in several variables like salinity, turbidity, resuspension/-deposition of the sediment, transport of pelagic organisms. Tide effects are almost exclusively due to M2 tidal cycle with a full tidal period covering just under 12.4 hours. For modelling purposes, the tide characteristics considered are summarised in Table 1.

A sampling program was carried out from June 1993 to June 1994 at three stations: river Pranto sluice, Armazéns channel mouth and Gala bridge. The river Pranto freshwater input was monitored (68 times during sluice openings), while in the other two sites the water exchanges, along tidal cycles (28 times), were quantified. Salinity, dissolved oxygen, pH, temperature and nutrients concentrations in the water column were also monitored with a 30 minutes periodicity. The field data were used to define the boundary conditions of the hydrodynamic model.

A large part of the southern arm intertidal area still remains more or less unchanged, having sand muddy bottoms covered by *Spartina maritima* marshes and *Zostera noltii*

Table 1 Tidal averaged levels (m) at Figueira da Foz harbour (June 1993–June 1994)

Maximum level		3,7
Mean level		2,0
Minimum level		0,3
Spring tide	Flood tide	3,5
	Ebb tide	1,3
Neap tide	Flood tide	2,7
	Ebb tide	0,8
Selected tide	Flood tide	3,3
	Ebb tide	0,7

meadows, but macroalgae blooms of *Enteromorpha* spp. have been regularly observed during the last 15 years. This is probably a result of excessive nutrient release into the estuary, coupled with longer persistence of nutrients (nitrogen and phosphorus) in the water column (Marques *et al*., 1997, Pardal *et al*., 2000, Flindt *et al*., 1997) and the silting up of the upstream area. Nevertheless, such macroalgae blooms may not occur in exceptionally rainy years (e.g. year 1994) due to low salinity for long periods, as a result of the Pranto river discharge (Pardal, 1998, Pardal *et al*., 2000, Martins *et al*., in press, Lillebø *et al*., 1999).

The benthic communities were monitored in the Mondego estuary, from January 1993 to June 1994 (Figure 3), during low water tide, at three different sites along an estuarine gradient of eutrophication in the south arm of the estuary (Figure 1): from a non eutrophicated zone (site A), where a macrophyte community (*Zostera noltii*) is present, up to a strongly eutrophicated zone (site C), in the inner and shallower areas of the estuary, where the macrophytes disappeared while *Enteromorpha* spp. blooms have been observed during the last 15 years. In this area, *Enteromorp*ha spp. biomass normally increases from early winter (January/February) up to July, when an algae crash usually occurs due to anoxia and most of the biomass is washed out to the Atlantic.

Models description

SMS (BOSS SMS, 1996) was designed as a comprehensive hydrodynamic modelling system being a pre- and post-processor for two-dimensional finite element and finite difference models. Interfaces have been designed to be used with the programs RMA2 and RMA4 (US WES-HL, 1996).

The hydrodynamic model RMA2 is used to compute water surface elevations and flow velocities for shallow water flow problems. This program solves the depth-integrated equations of fluid mass and momentum conservation in two horizontal directions by the finite element method using the Galerkin Method of weighted residuals. The elements may be one-dimensional lines or two-dimensional quadrilaterals or triangles, even with parabolic sides. The shape functions are quadratic for velocity and linear for depth. Integration in space is performed by Gaussian integration and derivatives in time are replaced by a nonlinear finite difference approximation. It is not applicable to supercritical flow problems. The quality model RMA4 is an interface used to assess the migration and dissipation of a constituent, describing its concentration in two horizontal directions as a function of time and place. It uses the hydrodynamic solution from RMA2 to define a flow velocity field for a given mesh and also reads a set of user-specified point loads as input.

Influence of salinity on macroalgae growth

In the south arm of Mondego estuary the usual salinity variation ranges from 20 to 30 psu. Nevertheless, in some years with rainy winters followed by rainy springs, salinity may vary between values of 1 and 20 psu, with an average value of 11 psu. In this situation, the spring

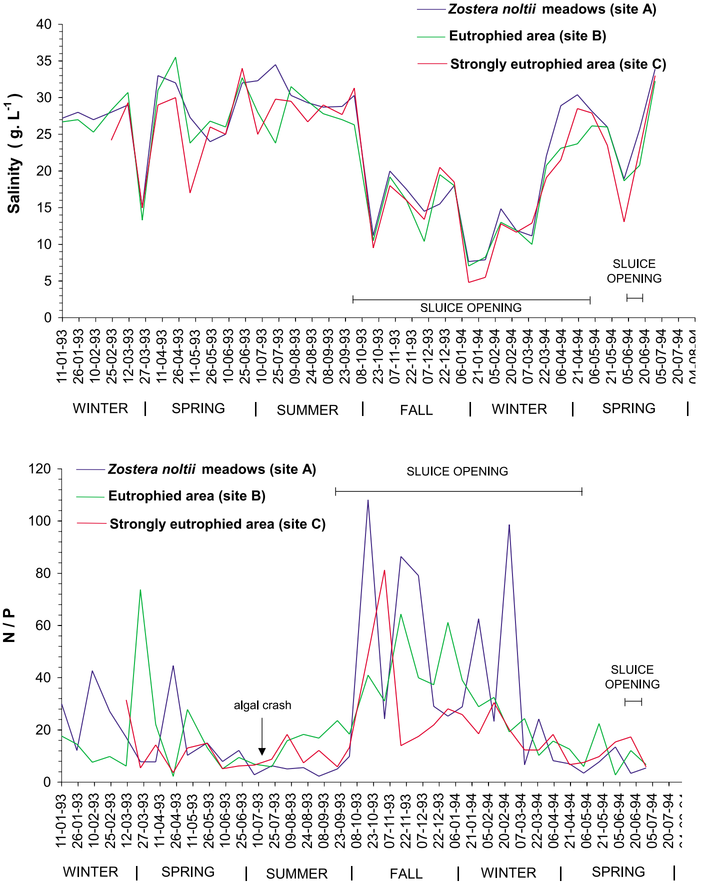

Figure 3 Sampling data (salinity and N/P ratio)

bloom of *Enteromorpha intestinalis* is not observed which may be related with its low ability to grow under low salinity conditions (Martins *et al.*, 1999). Moreover high precipitation also contributes to an accentuated reduction of light in the water column and to increased water speed and sediment turbulence, as well as to a high drifting of macroalgae to the ocean and to less favourable settlement conditions for young individuals (Lowthion *et al.*, 1985).

An early work (Martins *et al.*, 1999) was developed in order to understand the salinity influence on macroalgae growth and increase the knowledge on eutrophication processes in this estuarine system. It was demonstrated that salinity is an important parameter that controls growth *of E. intestinalis* populations from the south arm of the Mondego estuary. But, the effective values of growth are dependent on the existing conjugation of external factors (e.g. light, temperature, water velocity, sediment turbulence). Under non-limiting nutrient conditions and considering a salinity variation from 0 to 30 psu, *Enteromorpha intestinalis* shows higher growth rates within the salinity range of 10 to 22 psu and the optimum range seems to be situated between 17 and 22 psu. At salinity greater than 28 psu, growth is also decreased but the decrease is not as accentuated as for low salinity. The critical value for growth inhibition seems to be 3 psu. The occurrence of high salinity (>28 psu) during spring may not be so adverse to *Enteromorpha* growth, since values of 29 psu were registered during the spring bloom. Furthermore, during that period, salinity was never lower than 15 psu. Thus, at the south arm, any external factor that controls the values of salinity will also control (to a certain extent) the growth of *E. intestinalis*. This means that the eutrophication process is dependent on the hydrodynamics, which is influenced by the precipitation regime of each year.

Residence times

Residence times (RT) are broadly recognised as important descriptors of estuarine behaviour, but no real consensus exists on its definition. Traditionally, a single value has been used for RT evaluation in estuaries to characterise the whole system (Officer and Kester, 1991). This procedure, assuming steady state and well-mixed conditions is attractive to establish comparisons among systems and to estimate ecological quantities (Delesalle and Sournia, 1992). Local analysis is necessary to address important ecological local problems or resulting from local physical processes (e.g., turbidity maximum). Time variability of the environmental forcings also makes RT strongly dependent on the release time (Oliveira and Baptista, 1997).

In this work, a sensitivity analysis on RT spatial variability was performed. The effect of various factors (river flow discharge, release time, discharge tracer duration, and tracer mass) was anticipated for invariable tidal conditions. For each point of the physical system, RT was considered as the time period in which the conservative and once-through tracer concentration remains higher than its initial concentration in the system. This concept can be considered as a simplified approach methodology provided that baroclinic and wind forcing were not accounted for, and river Pranto flow and tidal cycle time variability were also neglected. Reentrant and non-conservative tracers behaviour and the effect of other factors like injection point location and river Pranto sluice opening regime will be considered in further research work.

Results and conclusions

The estuary hydrodynamic model based on the RMA2 program was implemented to compute water levels and mean velocity fields, resulting from the tidal and the river Pranto flow forcing. This system, with a total area of about 1,89 km^2, was discretized using a 2D mesh (Figure 4) composed of 3,371 triangular finite elements with 7,020 nodes. Two open boundary conditions were considered: the water surface elevation, defined according to the characteristics of a semi-diurnal M2 selected tide, imposed downstream of Gala bridge and a constant flow boundary condition upstream at the river Pranto entrance.

An important intermediate hydrodynamic result is the pattern and the magnitude of estuarine velocity currents. Indeed, for estimation of the potential drift of the opportunistic macroalgae a simultaneous experimental study is being carried out in order to relate the mean current velocities with the critical bottom stresses for *Enteromorpha* drifting. Figure 5 presents the simulated results of water depth and velocity field for the three most representative instants during the tidal cycle.

Calibration procedure was performed comparing measured values of velocity and salinity in a few stations with simulated model results. Calibration will be improved when more field data become available.

The simulated scenarios worked out are summarised in Table 2. River Pranto flow variation, mass of tracer injected, time release and tracer discharge were considered in order to assess their effects on spatial estuary residence times variability.

RT obtained from the different simulated scenarios allow us to establish the most sensitive zones to estuarine eutrophication processes, assuming that nutrients enrichment can be simulated by the tracer presence in most vulnerability zones of the system. Samples of the obtained results for different effects of simulated factors, considering the river Pranto flow value of 5 m^3/s, are depicted in Figure 6.

The effect of tracer discharge duration can be seen comparing scenarios S1–S5. Scenarios S1–S2 illustrate the time-release effect during ebb tide. Tracer mass variation

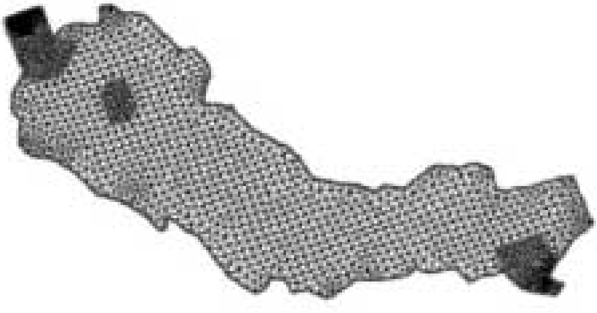

Figure 4 Finite element mesh

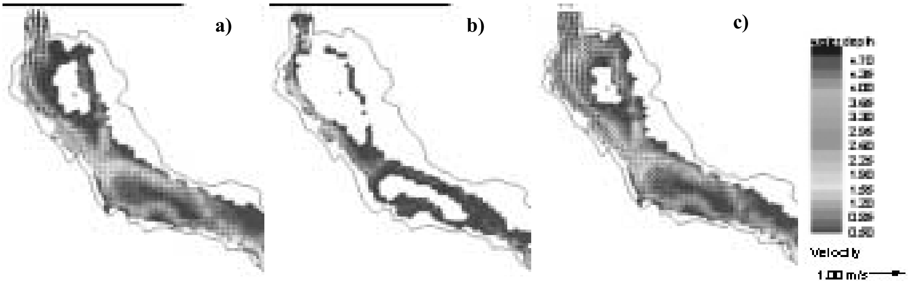

Figure 5 Water depths and velocity fields: a) half; b) three-quarter; c) tidal period

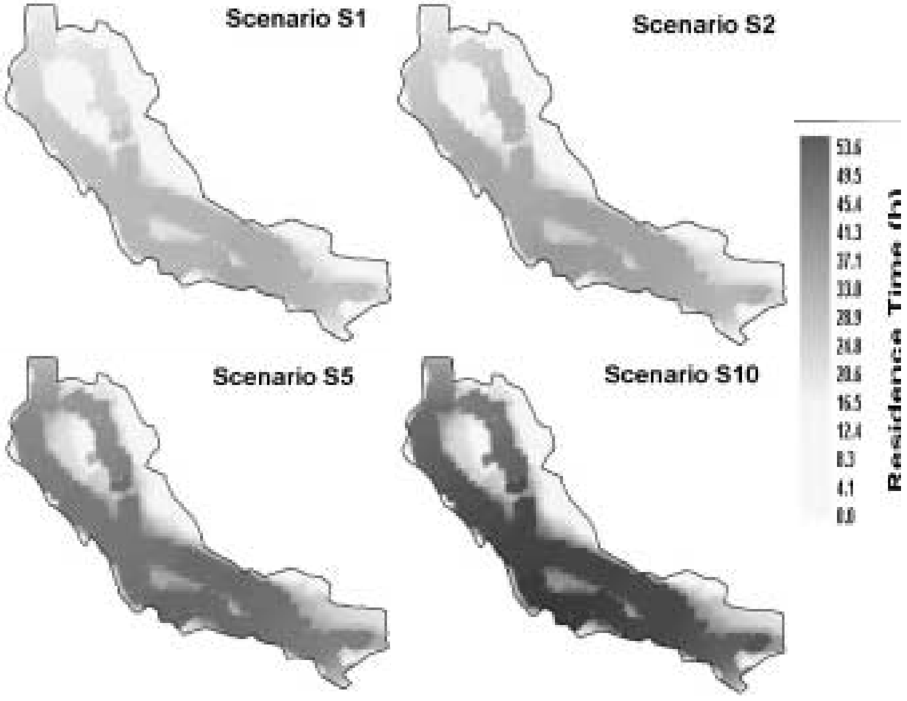

Figure 6 Residence times spatial variation

discharge effect can be analysed by means of scenarios S5–S10. In these conditions, discharge tracer duration appears to be a key parameter for residence time variation. So, when necessary, it is preferable to do more sluice openings, but during a shorter period of time.

Table 2 Simulated scenarios for the selected tide

River Pranto flow [m^3/s]:	5				10			
Tracer mass [kg]:	1800		3600		1800		3600	
Release Time (h)	6	9	6	9	6	9	6	9
Tracer discharge duration (h)								
1	S 1	S 2	S 6	S 7	S 11	S 12	S 16	S 17
3	S 3	S 4	S 8	S 9	S 13	S 14	S 18	S 19
6	S 5	–	S 10	–	S 15	–	S 20	–

Although these results can be taken as a first approximation, they represent an important step for time scale definition of eutrophication processes in estuary systems. Modelling results confirm the eutrophication gradient measured in the south arm of the river Mondego estuary, validating the methodology applied.

Since river Pranto is artificially controlled by sluices, the results obtained in this work and its future developments will constitute an important input for optimised operation policy of those hydraulic structures, in order to reduce the negative impact of nutrients discharges from this river in the estuarine system.

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